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Abstract

We will develop remote sensing methods to conduct environmental assessments in the riparian corridor of the Colorado River delta, shared by the United States and Mexico. This important regional ecosystem is dependant upon US water flows, yet the most important wildlife habitats are in Mexico. The delta region is poorly known and difficult to monitor on the ground. We will use ground-validated, aerial and satellite methods to develop accurate vegetation and habitat maps and predictive hydrological and vegetation models of this ecosystem in response to US flood releases. The work products will advance our understanding of water resource issues in dryland climates and provide a specific application tool for a critical binational natural resource area.

Specific objectives and examples of approach are:

1. Develop **vegetation and habitat maps** of the Colorado River delta in Mexico using geographically comprehensive data acquisition strategies at the ground, aerial and satellite levels (e.g., integrating locational data (i.e, GPS), transect data, ancillary maps at different spatial and temporal scales in a GIS (i.e., building upon the Lower Colorado Accounting System, Bureau of Reclamation), laser altimetry, multi-band digital cameras and radiometers from aircraft, and ETM+, MODIS sensors from satellite).

2. Develop a **surface hydrology model of the flood plain** and delta of the Colorado River in Mexico in different flood stages, using ground data, historic flow data, laser altimetry from aircraft (present) and LightSAR from satellite (future), and higher spatial resolution sensor data to include both ETM+ and MODIS for comparing flood magnitudes at different scales.

3. Conduct **change analyses of the vegetation response (consequence) to flood flows (cause)** using ground vegetation surveys, historic flood flow event reports, and vegetation indices from satellite images to determine not only the extent and magnitude of vegetation change, but also to create a predictive model of these land-cover, land-use change dynamics and to make assessments of endangered species habitat.

4. Develop a validated method to **estimate water stress and evapo-transpiration of vegetation** in the delta in an effort to obtain a water balance map product using ground-based sap flow meters and sensors on aircraft and satellites which have visible, near-infrared, and thermal channels.

5. Combine 1-4 into a predictive surface **hydrology - vegetation - habitat model**, that uses as input flow releases from the United States to Mexico and has output predictions of extent of vegetation cover and of specific vegetation units associated with wildlife habitat values.

6. Develop an on-going **monitoring protocol** to (i) improve the management of this semiarid ecosystem for both sustainability and resilience of the natural resources (i.e., water), (ii) further the understanding of the consequences of land-cover and land-use change on habitat value using remote sensing methods, and (iii) provide synergy among energy, carbon, and water cycles, vegetation spatial variability, economic models, and societal responses.

Technical Plan

I. Background:

Arid and semi-arid zone riparian corridors are among the most important yet threatened natural ecosystems on Earth. They are important because they provide water, food and migration routes for wildlife in otherwise dry habitats; they are threatened because diversion of water for human use and flow-regulation to control flooding have severely degraded the habitat value of virtually all the world's perennial dryland rivers (Dynesius and Nilsson, 1994). Riparian corridors are linear landscape features that connect ecosystems across regions. Hence, the deterioration of riparian habitat may affect populations of migratory species at continental or even hemispherical scales. They are among the most sensitive ecosystems to global change and, as hotspots of productivity, they are important components of dryland carbon cycles. Remote sensing should be among methods of choice for monitoring riparian zones, since these corridors stretch over thousands of kilometers, cross national borders and are difficult to survey on the ground. However, remote sensing is still not much used in the management of riparian zones. As narrow features with complex mixes of vegetation, water and soil, they have been considered difficult targets for analysis by satellite imagery.

Our proposed study area is the lower Colorado River below Lake Mead to the delta where the river enters the Gulf of California in Mexico. This river stretch is a key binational resource for maintaining species diversity of 45 sensitive, threatened or endangered plants and animals (Glenn et al., 1996, 1998). Remote sensing methods have been partially developed for the U.S. portion of river via the Lower Colorado River Accounting System (LCRAS)(Figure 1)(U.S. Department of Interior, 2000) but they are now especially needed for monitoring the delta region of the Colorado River in Mexico (Figure 2). This area has been incorporated into a UNESCO Biosphere Reserve, and it contains the largest remaining populations of most of the sensitive species listed for the US stretch of river, yet it has been so little studied that new wetland and riparian habitats are still being discovered and named. Ground studies are difficult due to the vastness of the area, the severe desert climate and the lack of roads. US scientists do not have routine access to the study area, but as explained in the next section, this entire ecoregion is dependent on flows of water released from the United States to Mexico. US and Mexican water and resource management agencies need common tools for monitoring this ecosystem across borders.

Our group has conducted 4 years of ground and remote sensing studies on the lower Colorado River in the United States and its delta in Mexico (Nagler et al., submitted; Zamora-Arroyo et al., in press). These preliminary studies (funded by U.S. Fish and Wildlife Service, Bureau of Reclamation and private environmental groups) have developed ground, aerial and satellite methods to conduct change analysis of vegetation dynamics as affected by flood flows. We propose to build on the preliminary research to develop non-intrusive, satellite-based remote sensing methods to monitor ecosystem stress and water requirements of the riparian and wetland habitats, as affected by river operations decisions in the United States and Mexico. The products will include species-level vegetation maps; change analysis of vegetation and habitat value as affected by river flow; calibrated methods to estimate water stress and evapo-transpiration from thermal bands; and a hydrological model relating surface flows to extent of overbank flooding and subsequent vegetation response.

These products are urgently needed by United States and Mexican natural resource management agencies and non-governmental environmental groups concerned with conservation in the lower Colorado River ecoregion. US and Mexico federal and state agencies as well as non-governmental environmental groups, at a special stakeholders' meeting on the Colorado River delta convened by Deputy Secretary of the Interior Hayes (October, 2000), concluded that a hydrological and vegetation/habitat model is the first research priority in understanding the responsibility of the United States in maintaining and enhancing this ecosystem (Appendix A).

II. Scientific and Applications Relevance

Description of the Ecosystem:

The riparian corridor of the lower Colorado River was historically a mixture of gallery forest habitat (cottonwood and willow trees) interspersed with backwater wetlands (dominated by cattail and other emergent plant species). These habitats were maintained by the natural flow regime, which consisted of spring floods that brought water out of the main channel to wash salts from the banks, germinate tree seeds, and create seasonal wetlands.

With construction of dams and diversion of water for human use, the flow regime has been stabilized on the U.S. portion of the river. Overbank flooding is now rare, and as a result the gallery forests of cottonwood and willow have been nearly completely replaced by salt tolerant shrubs, particularly salt cedar (*Tamarix ramosissima*), an invasive, exotic species from Eurasia (Ohmart et al., 1988). Since the river remains within its channel, only a few large wetland areas remain on the river. Migratory song birds that depend on the forested part of the riparian corridor as a migration route have been negatively impacted by the changes, as have nesting water birds that depend on the thick cattail marshes (U.S. Bureau of Reclamation, 1996).

The situation is different in the delta region of the river in Mexico. Two sources of water from the United States have partially revived the riparian and wetland habitats of the delta over the past 25 years. Until recently these effects have gone unnoticed, but the delta is now recognized as containing the largest remaining reservoirs of riparian and wetland species diversity in the lower Colorado River ecoregion (Glenn et al., 1996, 1998; Zamora et al., in press). The first water source is agricultural drain water from the Wellton-Mohawk Irrigation District in Arizona. This water (ca. 160×10^6 m^3/year) flows via lined canal into Mexico where it has created Cienega de Santa Clara, a 4,200 ha wetland which is now the largest brackish marsh habitat in the Sonoran Desert. It supports over 6,000 individuals of the endangered Yuma clapper rail (compared to less than 1000 left in the United States). It also supports thousands of resident and migratory waterfowl, raptors, fish and mammals which require marsh habitat. The second water source is occasional flood releases from Lake Mead during El Nino cycles. This water enters the normally-dry channel of the Colorado River then flows to the sea. During the period 1964-1981, Lake Powell was still filling behind Glen Canyon Dam, the last major impoundment built on the river. During those years, excess water above human demand was simply stored in the still-filling reservoir and the delta experienced a prolonged dry period. After Lake Powell reached capacity in 1981, there have been water releases to the delta in 1983-1988, 1993 and 1997-1999. Our preliminary studies have shown that these flood releases have brought about a resurgence of native cottonwood and willow trees in the riparian corridor. We have estimated that the riparian corridor below Morelos Dam now contains 3 times as much cottonwood and willow habitat as the US stretch of river below Davis Dam, which is five times longer than the stretch in Mexico.

Problem Statement:

The reestablished riparian and wetlands habitats in the delta are the inadvertent creation of US and Mexico water management decisions. They are not formally part of the river management plan, even though great effort is now expended to preserve smaller pockets of similar habitat on the US part of the river to comply with the Endangered Species Act. The Department of Interior, through the Fish and Wildlife Service and Bureau of Reclamation, and the Department of State, through the International Boundary and Water Commission (IBWC), have created a mechanism for working with Mexico to define the water and management needs of these habitats. Specifically, they have created a "Fourth Working Group" within the IBWC to gather information on the delta habitats and develop a conservation scheme. The most immediate research need is a hydrological and habitat model of the delta, which can predict changes in habitat value as a function of US water flows. How much water is needed from the United States, and on what delivery schedule? Answering these questions will require reverse and forward-looking change analyses of the delta habitats in response to flood flows and agricultural drain water deliveries. We propose to develop remote sensing methods to accomplish these goals.

III. Objectives:

1. Develop **vegetation and habitat maps** of the Colorado River delta in Mexico using geographically comprehensive data acquisition strategies at the ground, aerial and satellite levels (e.g., integrating locational data (i.e, GPS), transect data, ancillary maps at different spatial and temporal scales in a GIS (i.e., building upon the Lower Colorado Accounting System, Bureau of Reclamation), laser altimetry, multi-band digital cameras and radiometers from aircraft, and ETM+, MODIS sensors from satellite).

2. Develop a **surface hydrology model of the flood plain** and delta of the Colorado River in Mexico in different flood stages, using ground data, historic flow data, laser altimetry from aircraft (present) and LightSAR from satellite (future), and higher spatial resolution sensor data to include both ETM+ and MODIS for comparing flood magnitudes at different scales.

3. Conduct **change analyses of the vegetation response (consequence) to flood flows (cause)** using ground vegetation surveys, historic flood flow event reports, and vegetation indices from satellite images to determine not only the extent and magnitude of vegetation change, but also to create a predictive model of these land-cover, land-use change dynamics and to make assessments of endangered species habitat.

4. Develop a validated method to **estimate water stress and evapo-transpiration of vegetation** in the delta in an effort to obtain a water balance map product using ground-based sap flow meters and sensors on aircraft and satellites which have visible, near-infrared, and thermal channels.

5. Combine 1-4 into a predictive surface **hydrology - vegetation - habitat model**, that uses as input flow releases from the United States to Mexico and has output predictions of extent of vegetation cover and of specific vegetation units associated with wildlife habitat values.

6. Develop an on-going **monitoring protocol** to (i) improve the management of this semiarid ecosystem for both sustainability and resilience of the natural resources (i.e., water), (ii) further the understanding of the consequences of land-cover and land-use change on habitat value using remote sensing methods, and (iii) provide synergy among energy, carbon, and water cycles, vegetation spatial variability, economic models, and societal responses.

IV. Technical Approach:

General. We plan to fly short and extended transects around the core study areas with a "MODIS Quick Airborne Looks" (MQUALS) package consisting of Exotech radiometers with TM and MODIS filters, an infrared thermometer, and a multispectral (blue, red, NIR) camera, mounted on a small aircraft. The MQUALS sensor package will be used to acquire overlapping, 1,000 m, aerial imagery and 'calibrated' top-of-the-canopy reflectance measurements of the Colorado River floodplain. To the extent possible, these data will be collected concurrently with ETM+/ MODIS overpasses and ground data collection. Processing of the radiometric data would rely on ground measurements made over a calibrated 'spectralon' reference panel and cross-calibration of the sensors to a standard reference panel housed in the Optical Sciences Center (Dr. Kurt Thome) at the University of Arizona. The MQUALS package, not only documents surface conditions at fine spatial resolution (< 0.5 m), but also enables the determination of percent vegetation cover, soil type, soil salinity, and species composition. MQUALS also provides a mechanism for up-scaling ground measurements and aircraft-based 'reflectance' and 'emittance' measurements to image-based resolutions (e.g. ETM+, MODIS) for region wide monitoring purposes.

Through the 'Terrestrial Biophysics and Remote Sensing' computing facility, we will acquire 16-day composited MODIS surface reflectances and vegetation indices on a continuous basis starting from June 2000. This data will be at the enhanced, 250 m pixel resolution with some of the bands (blue, green, and middle-infrared) sharpened from 500m to 250 m. Preliminary analyses of this area has shown the tremendous value of 250 m data in capturing the seasonal-temporal dynamics of the overall floodplain. The MODIS data is already calibrated and corrected for atmosphere effects, particularly with its narrow near-infrared bandpass which is essentially free of water vapor influences. The temporal sensitivity of the 16-day MODIS time series will allow us to monitor the Colorado delta and floodplain on a continuous basis for the detection of "hotspots" for more detailed analysis. In such cases, we will purchase and utilize Landsat ETM+ imagery for the more intensive analysis. Depending on the severity and type of 'change', we may also employ the rapid response, MQUALS light-aircraft, sensor package for a flyover within 1 - 2 weeks.

The combined ETM+/ MODIS data monitoring protocol, integrated with the MQUALS package, becomes a powerful methodology for studying the dynamics of water flow and vegetation responses along the Colorado River floodplain.

1. Vegetation and habitat maps.

Preliminary research (Nagler et al., submitted) established a strong correlation between percent vegetation cover measured on the ground and the normalized difference vegetation index (NDVI) of Red/NIR band images taken from a low-level (150 m) airplane survey of the flood plain ($r^2 = 0.84$)(Figure 3). Further, the major plant associations (groundcover species, saltcedar-arrowweed, emergent plants and native trees) contributing to different habitat values could be visually differentiated on the images. Comparison of NDVI values for common landscape features (water, soil, vegetation) for aerial images and a TM of the same scene taken near the time of the flight gave nearly identical values (Figure 4), showing that results can be accurately scaled from ground, to aerial and then satellite images (Zamora et al., in press).

We will build on this data to develop vegetation maps and habitat maps at four seasons of the year, corresponding to summer (June 21), fall (Sept. 21), winter (Dec. 21) and spring (March 21), each year for the three years of the study. We will use the MQUALS sensor package (Huete et al., 1999) to acquire overlapping, 1,000 m aerial images of the floodplain, using multi-band (blue, red and NIR) and visible-band digital cameras. The MQUALS system incorporates paired, ground and airborne sensors such that voltages can be converted into actual reflectance values for radiometric measurements. We will use visual interpretation of the images to construct a **vegetation base map**, dividing each image (representing ca. 100 ha) into 100, 1-ha mapping units, categorizing each unit as soil, water or vegetation, and if vegetation as groundcover, shrub, native tree or emergent aquatic species. Using NDVI and other vegetation indices and cluster analyses, we will develop methods to accurately map units based on spectral properties, then we will scale up to larger-scale mapping units for TM images of the same scenes. Ground truthing will consist of locating representative sample areas on the ground and quantifying vegetation (by type), soil and water using line-intercept methods. Other biophysical measurements on the ground will include: global and local Leaf Area Index by LiCor2000 calibrated by physical measurement of LAI for subsamples of each species and, reflectivity spectra of leaves of each plant type as well as soil, water and litter at 490-990 nm in 10 nm increments by hand-held radiometer.

A larger scale **habitat map** will be developed by classifying each image representing 100 ha into habitat classes as defined by Ohmart et al., (1988) for the lower Colorado River. These classes include open and closed gallery forest, shrub-dominated, aquatic and emergent marsh associations, each divided into sub-categories and each with particular wildlife habitat values for relevant species. This type of mapping has been conducted for the lower Colorado River in the United States using visual interpretation of conventional aerial photographs, but has not been done by spectral methods or scaled to satellite images.

Within 2 weeks of each seasonal flight, a TM-3 and MODIS image of the floodplain will be acquired. Digital numbers will be converted to exoatmospheric reflectance values, and NDVI values calculated for each pixel of the image. The TM will not have sufficient detail to differentiate different plant associations, but when overlaid on the photomosaic there will be a correspondence between NDVI values and underlying vegetation units. The photomosaic base map and corresponding classified ETM+ and MODIS images can then be used for subsequent change analysis, over seasons and years. This analysis assumes that the basic vegetation structure in the delta changes only slowly, an assumption which has proven valid over twenty years of monitoring on the US stretch of the lower Colorado River. Therefore, an aerial-based photomosaic used to classify vegetation types will be valid for many years, while more frequently acquired satellite images can be used to detect changes in biomass coverage and intensity with vegetation units.

2. Surface hydrology of the floodplain.

A **two-dimensional model** of the floodplain will be constructed, correlating the rate of past flow events (1980-1999), in $m^3 sec^{-1}$, with wetted area in the floodplain, determined by analysis of historic TM images. This model will be useful in predicting the flood hazards and environmental effects of US water releases. A **three-dimensional model** will then be constructed by determining current elevations within the flood plain, to predict not only wetted area but also the volume of water contained in the flood plain at different flood stages. This model can be used to predict flood effects even when the topography of the delta changes due to siltation and channel alteration. Elevations will initially be determined using ground-validated, light aircraft methods. A light aircraft will fly numerous transects across the flood plain at a height of approximately 1000 meters above ground, using a laser rangefinder to determine the instantaneous distance between the floodplain surface and the aircraft. These distance measurements will be performed at one second (50 meter) intervals, and have an accuracy of +- 1 meter.

The parameter of primary interest is the variation in the depth of the floodplain channel across a transect, which can be determined independent of knowledge of the absolute height of the banks of the channel. The aircraft will be flown at a constant pressure altitude, using an electronic (piezoelectric) altimeter/barometer providing height readouts with 1 meter resolution, and an accuracy of +- 3 meters. Since only a small amount of instrument drift in the altimeter readings is expected during any given transect, the channel depth profiles should have errors of the order of 2 meters, while the height of the banks could be uncertain to within 4 meters. However, the absolute height of the river bank at various locations can be deduced from selected measurements taken on the ground, coupled with examination of the entire set of channel profiles. The GPS altitude of the aircraft will also be recorded at 1 second intervals, although this is not expected to have the same resolution as the barometric altitude. We have examined the option of flying a synthetic aperture radar (SAR) installed in a light plane, but have decided that the added expense and poorer height resolution were not offset by the broader width of the channel profiles that could be obtained using SAR. Additionally, a single light aircraft can simultaneously fly the laser profiler system and the digital cameras needed to collect vegetation data, but the SAR system is so large that no additional remote sensing equipment could be co-located on a light aircraft.

In the future, LightSAR data and the current data, collected from both (i) a ground-based, local, study area and from (ii) aircraft altimeter data of multiple transects which give a profile of the ground elevation across the main channel of the river, will be compared to best characterize the Colorado River channel in Mexico and its delta.

3. Vegetation change analysis.

Change detection involves the use of multitemporal data sets to discrminate areas of land cover and/or soil-related change. We are interested in separating out the changes of interest from all changes taking place. We expect that the use of vegetation indices will isolate changes in temporal and spatial vegetation variations. We will also search for the appropriate band combinations and to differentiate flooding events and vegetation responses. Careful attention will be placed to ensure that the changes in spectral reponses and/ or indices are indeed attributable to a change in land cover and not due to extraneous factors such as solar angle (time of day) or atmospheric conditions.

Bureau of Reclamation reports of the historic flow events in the last 20 years will provide information on the period and magnitude of the anthropogenically-caused flooding. Correlating these pulse floods with images of the delta in the post-flooding period gave an overview of the effect of the flooding on semiarid riparian vegetation extent and habitat, and provided a high correlation ($r^2 = 0.931$) between percent vegetation and the years of flow (Fig. 5) (Zamora et al., in press). That study concluded that less than 1% of the base flow of the river is required to support the regeneration of native trees by washing salts from the banks and allowing mesophytic species to be established, and thus it is possible to maintain a biodiverse ecosystem in this inherently variable semiarid zone. However, in years between flood events, when there is little to no water available, salts build up in the soils producing a salinity effect which reduces biodiversity; salt tolerant species such as the exotic *Tamarix ramosissima* (salt cedar) begin to fill the delta in a uniform pattern. We will produce maps of semiarid, riparian vegetation (habitat) land cover and land use change in response to available water (3-D model) contained in the flood plain at different flood stages. A predictive model of these land-cover, land-use change dynamics (cause and effect) will be built on the last 20 years of available data (historic flood flow event reports, and vegetation indices from satellite images). It will be used to make current assessments of endangered species habitat and a mosaic showing areas of fragmentation. The model will be useful for predicting the future status of biodiversity in the delta based on a minimum water requirement.

4. Vegetation water stress and evapotranspiration map product.

We will estimate water stress and evapo-transpiration of vegetation in the delta using ground-based sap flow meters and sensors on aircraft and satellites which have visible, near-infrared, and thermal channels, in an effort to obtain a water balance map product. Quantifying water balance in the Colorado River delta in Mexico serves (i) to protect biologically diverse areas and habitats for endangered species, and (ii) to protect human livelihood, which is dependent on properly managed water supply, by providing advanced notice of the water amount and availability, and (iii) to manage the social, economic, and demographic changes associated with land use.

The Crop Water Stress Index (CWSI) (Jackson et al., 1981; Idso et al., 1981) correlates water stress to temperature differences between the foliage and air with reference to the vapor pressure deficit and a crop-specific baseline. CWSI assumes 100% vegetation cover (no bare soil- a measurement not of evaporation, just transpiration because the difference between ET and T is minor for full-vegetation canopies) and is a good indicator of crop stress and thus water deficit.

However, CWSI also assumes that a measure of canopy temperature is available and that no soil background is showing because that would change the temperature measurement and give a false indication of water stress. Application of the CWSI is inhibited by its inability to measure foliage temperature of partially vegetated fields. Moran et al. (1997) state that the use of remote sensed crop coefficients (the ratio of actual crop ET and that of a reference crop) combined with readily available meteorological information is a useful application for the estimation of actual site-specific crop ET rate. Monitoring crop ET rates is important because transpiration decreases are indicative of stressed, diseased, or water deficient crops.

When temperature differences (°C) are plotted as a function of vapor pressure deficit, two theoretically-derived, distinct baselines for the maximum transpiration (stomates open) and minimum transpiration (stomates closed) conditions provide the upper and lower limits for a vegetation type's water stress. Canopy and air temperatures are measured with an Infrared Temperature Gun (IRT), either on the ground, pointing down on the full-canopy or with IR bands on a radiometric sensor or an airborne thermal imager. Vapor pressure deficit is the difference between the moisture inside and outside a leaf. When the vapor pressure inside and outside are the same, the deficit is zero (i.e., a humid environment); when the leaf is moister than the outside air, the deficit is negative. The greater vapor pressure deficits occur more frequently in places like the delta where you have very arid conditions and field-irrigated agricultural plots.

The Water Deficit Index (WDI) (Moran et al., 1994) can be used for evaluating evapotranspiration (ET) rates. It can be computed using remotely sensed measurements of surface temperature and reflectance with limited micro-meteorological data needed (only net radiation, vapor pressure deficit, wind speed and air temp). WDI is the ratio of actual to potential ET and provides estimates of the relative water status of a field having varying percent cover (0-bare soil to 1-full cover vegetation). This percent cover estimate is often approximated by a vegetation index, which is most often in the literature the Soil Adjusted Vegetation Index (SAVI) because SAVI is insensitive to soil brightness (Huete, 1988). The range of VI values falls between ~0.1 bare soil to 0.8 full cover vegetation. WDI is illustrated as percent vegetation cover as a function of canopy – air temperature differences (Clarke et al., 1994). As stomata open and conductance is high, more transpiration occurs and the plant is cooler relative to air temperatures, i.e., $T_c < T_a$ (negative or lower values) representing non-stressed conditions. The opposite occurs when stomata are closed; conductance and transpiration are close to zero, and the plant warms relative to the air, i.e., $T_c > T_a$ (positive or higher values) representing high-stressed conditions.

We will conduct evapotranspiration measurements concurrent with MQUALS overflights during the four seasonal campaigns described under Vegetation and Habitat Mapping. Continuous sap flow measurements will be made on 8 different plants of the 4 major riparian species (cottonwood, willow, salt cedar and arrowweed) over a 7 day period during the campaign, using the stem heat balance method (DynaMax, Inc.). Measurements will be made at one or more of the ground-truth sites corresponding to images recorded by the DyCam and visible-band cameras. The surface temperature and air temperatures in the delta over this period will be acquired with an infrared temperature gun (IRT) and thermocouples, respectively, to monitor WDI, which use canopy minus air temperatures in conjunction with the prediction of percent cover to determine water stress in plants. The WDI, which generally gives a rate of evaporative water loss from an area (mostly crop regions), will be tested in riparian zones which have a range of species and varying percent cover. On test plots of pure riparian species, sap flow was well correlated with ground-based canopy-air temperature changes using an IRT gun (Nagler, et al., 2001, unpublished). These relationships will be extrapolated to mixed scenes as observed from light aircraft by measuring canopy and air temperature from the air and sap flow at the ground on different species. Remote sensing measurements of canopy temperature will be taken from aircraft-borne IRT and by the thermal bands on ETM+ and MODIS.

This early detection field/aerial method for determining stress may validate satellite data anomalies, such as out of season VI, that may be correlated with water stress detected from MODIS or other products (VI, Vegetation Cover Conversion or Land Cover Change). Stressed areas determined using the CWI method from ground and aerial measurements will be detected far before the disappearance of vegetation is seen. Such a method will alert the public to the environmental risks of water stress before the livelihood of the citizens becomes a crisis. This public outreach would help in the planning for social, economic, and demographic change that usually follows from water loss - vegetation/habitat degradation.

With estimates of consumptive use (evapostranspiration), the rate of surface flow, and the storage capacity (volume) of the aquifer, we will have a better understanding of the overall surface water balance in the delta. Although we cannot measure the aquifer directly, remote sensing methods for measuring transpiration rate could provide an estimate of the water used by phreatophytic vegetation. If such a water budget product could indicate the status of water in the river basin by the health of the vegetation and the magnitude of land cover change, then, in times of a water stress alert, the acquisition of higher resolution satellite, aerial measurements, and field data would be initiated to quantify both the decline in total vegetation cover over time and the loss of native tree species. Highly validated data and fast turn-around on a water budget product in this sensitive area will ensure that the water requirements to support the ecosystem are fulfilled.

5. Surface hydrology - vegetation - habitat model.

The products developed in objectives 1-4 will be combined into a GIS which can be used as a management tool. We will use GIS analysis tools to develop a model similar to LCRAS that can predict consequences of flow releases to the delta in terms of flooding and vegetation response. Inputs into the model will include regression equations relating vegetation, evapotranspiraiton and flooded area to flow volumes and frequencies.

Hydrologic analysis tools will be implemented in a raster-based GIS, such as ArcInfo's Grid module or ArcView's Spatial Analyst, to yield flow direction, flow accumulation and watershed layers within the floodplain. From the elevation data it will be possible to construct a three-dimensional surface model of the delta region and preform a volumetric analysis of past floods. These data can then be used to model other flooding scenarios using different configurations of elevation within the floodplain (elevations change temporally due to siltation and channel-clearing activities). These results can then be overlaid on the habitat and vegetation maps to predict consequences of flooding or channel alteration on areas of environmental concern.

A custom-built, simplified interface will be developed in ArcView to allow managers and researchers to use the GIS to predict the extent and duration of flooding as a function of flow releases, and predicted effects on vegetation and habitat. **Predictions of the GIS will be tested**

against future flow releases, allowing this product to be verified and refined, similar to LCRAS.

6. Monitoring protocol.

We will develop a simplified, satellite-based monitoring system for this riparian system, based on data collected in 1-5. Land cover change is fundamental to monitor because the riparian vegetation boundaries, percent cover, and acreage per species shrink or swell with the amount of water available. The overall purpose of monitoring the riparian zones in this arid region is to make a product that depicts the water stress of the ecosystem. Other dimensions of water sources can be monitored as well, like the river flow itself, surface wetness, and rainfall. This product would give information that enables monitoring of surface deliveries, storage in soil/riverbed, and seasonal and annual information on water balance and plant stress. The bio-diversity of the river system vegetation, the quality of the water, and the lack of fragmented habitat is fundamental to many species of migrating or nesting birds who use only these islands or pockets of land as breeding grounds. Riparian zone monitoring will provide information on the location, magnitude, and extent of vegetation, such as the acreage of land cover types such as soil, water, marsh, and land plant cover. Products such as vegetation indices (VI) or percent cover derived from VI, as well as extent of flooding and estimates of water stress and evapotranspiration can be acquired frequently at high resolution to produce a tight sinusoidal seasonal or annual curve from which vegetation maxima can be determined. This study will provide information as to the season in which one species reaches it's maximum, such that the end user may capture and use only those images in which the vegetation is peaking and make comparisons to other vegetation types or communities. By acquiring frequent coverage, we can provide a simplified protocol for resource managers to continue this monitoring without intensive ground-truthing; and, furthermore, preliminary areas that are seen peaking out-of-season with other vegetation areas can be earmarked for obtaining those spatial-temporal images for uses specified by the end-user.

V. Expected Significance / Deliverables:

Specific work products will include:

- Vegetation and habitat maps of the Colorado River delta in Mexico
- Volumetric capacity of the flood plain and delta of the Colorado River in Mexico in different flood stages
- Extent and magnitude of vegetation change
- Predictive model of these land-cover, land-use change dynamics to make assessments of endangered species habitat
- Method of validating water stress maps and species-dependent evapo-transpiration rate.
- Surface hydrology - vegetation - habitat model
- Monitoring protocol for managing water as a valuable natural resource, for managing endangered species habitat, for managing the integration of ecological systems, economic models, and societal responses.

This work will also contribute to the larger goals of NASA's Earth Science program by: 1) documenting an important regional component of primary productivity and the carbon cycle; and 2) developing a case study on predictive scenarios of LCLIC related to arid-zone water resources. The methods developed in this project will be applicable to riparian systems throughout the world's arid zones, and will represent an advance for remote sensing studies into this type of ecosystem.

VI. Interaction with End-Users for Type 1, Applications Program.

The applicants have an on-going participation with the remote sensing and vegetation mapping personnel in the US Bureau of Reclamation Lower Colorado Region. We have collected joint data sets representing multi-band and visible band digital images of the entire lower Colorado River system in both the US and Mexico. We are working with them to integrate our remote sensing products into their LCRAS and vegetation mapping systems. We will expand on this collaboration in the proposed research. All imagery collected in the project will be made available to BOR for inclusion in LCRAS. We will coordinate our mapping systems (methods of classifying vegetation associations and habitat pathces) with those developed by BOR and used by agency biologists. GIS systems developed to display and interpret data will be compatible with products and procedures used by BOR. LCRAS has moved beyond the research and development stage to the demonstration stage. By project end, we expect that the delta region of the river in Mexico will be an important new component of LCRAS and will be ready for the implementation stage.

Figure 1. Location map showing the Lower Colorado River Accounting System study area in the United States (US Department of Interior, 2000).

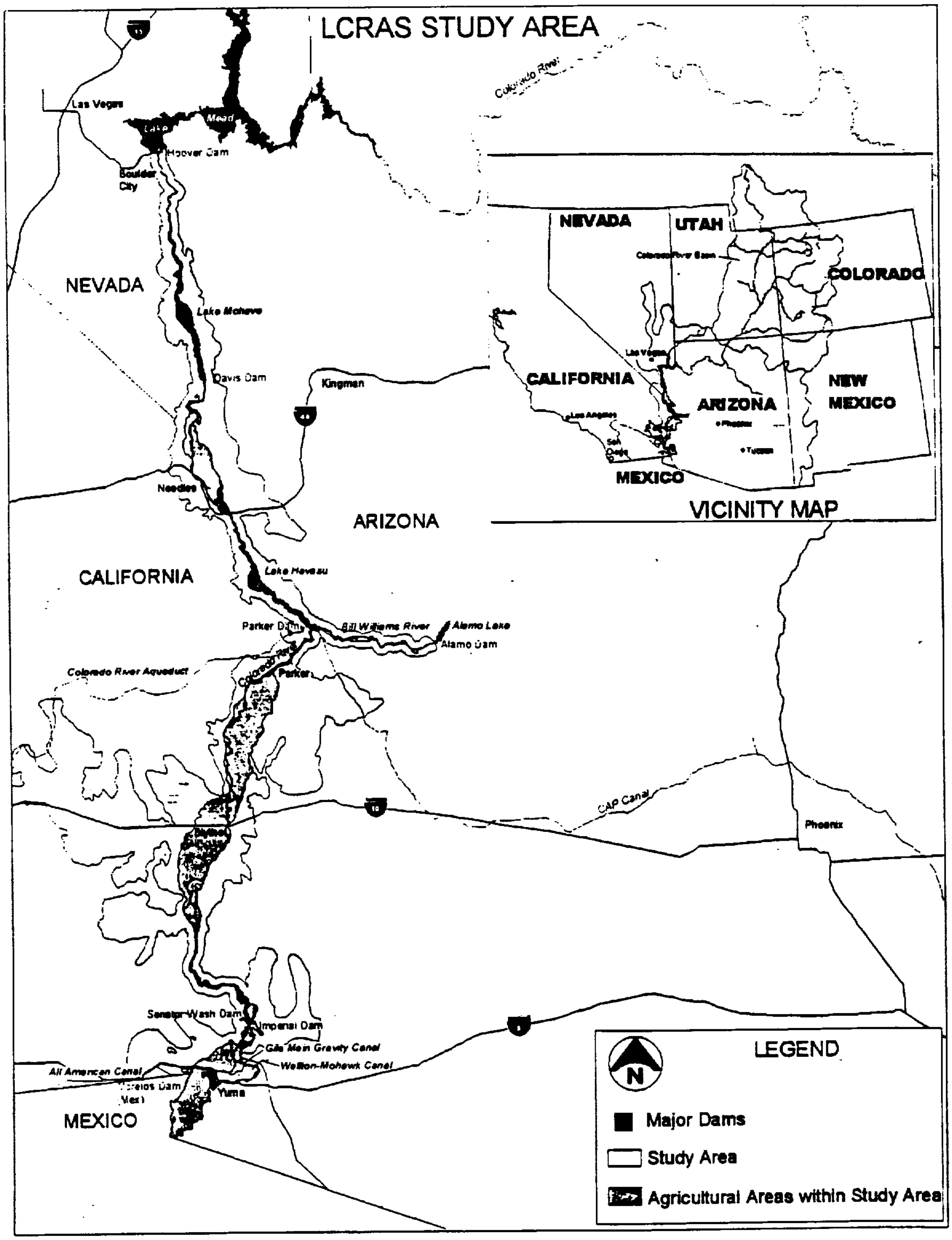


Figure 2. The Colorado River delta, Mexico, showing location of samples sites surveyed in preliminary research. Lines indicate where strings of DyCam muti-band images were acquired by light aircraft at 150 m May 24, 1999. Triangles show where cross-river ground transects were established June-July, 2000. Circles show where well points were placed into the aquifer. The grey area of flood plain is the cottonwood-willow zone, while the stripped area is salt cedar and intertidal habitat. Also shown is Cienega de Santa Clara, a wetland created in Mexico by US agricultural drain flows.

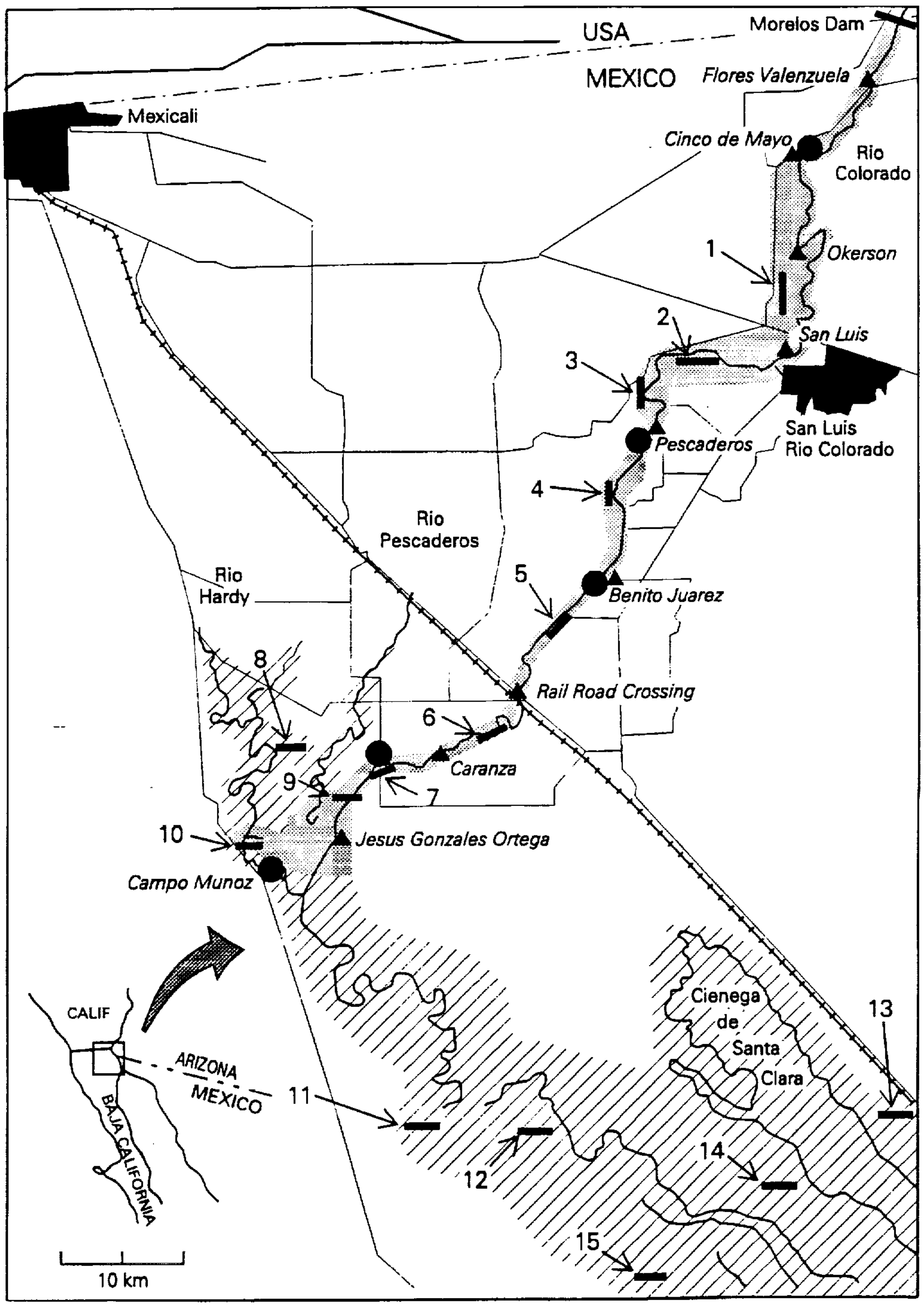


Figure 3. Regression equations between % vegetation cover on 63 DyCam images obtained over the delta by light aircraft and three Vegetation Indices (NDVI, SAVI and EVI) based on blue, red and NIR bands.

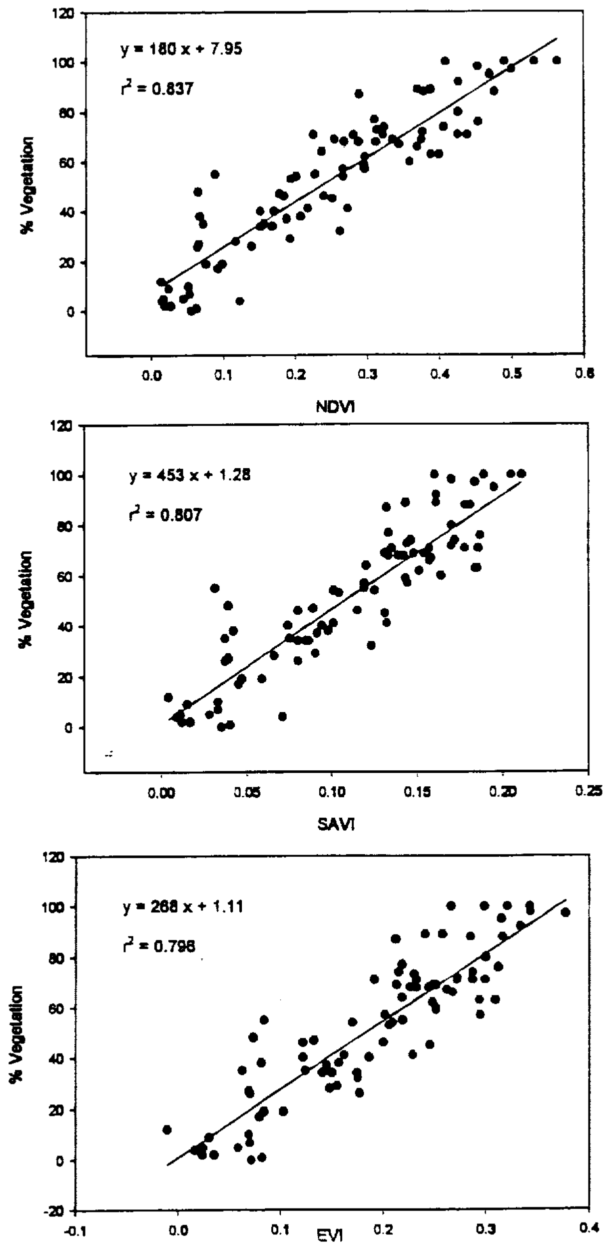
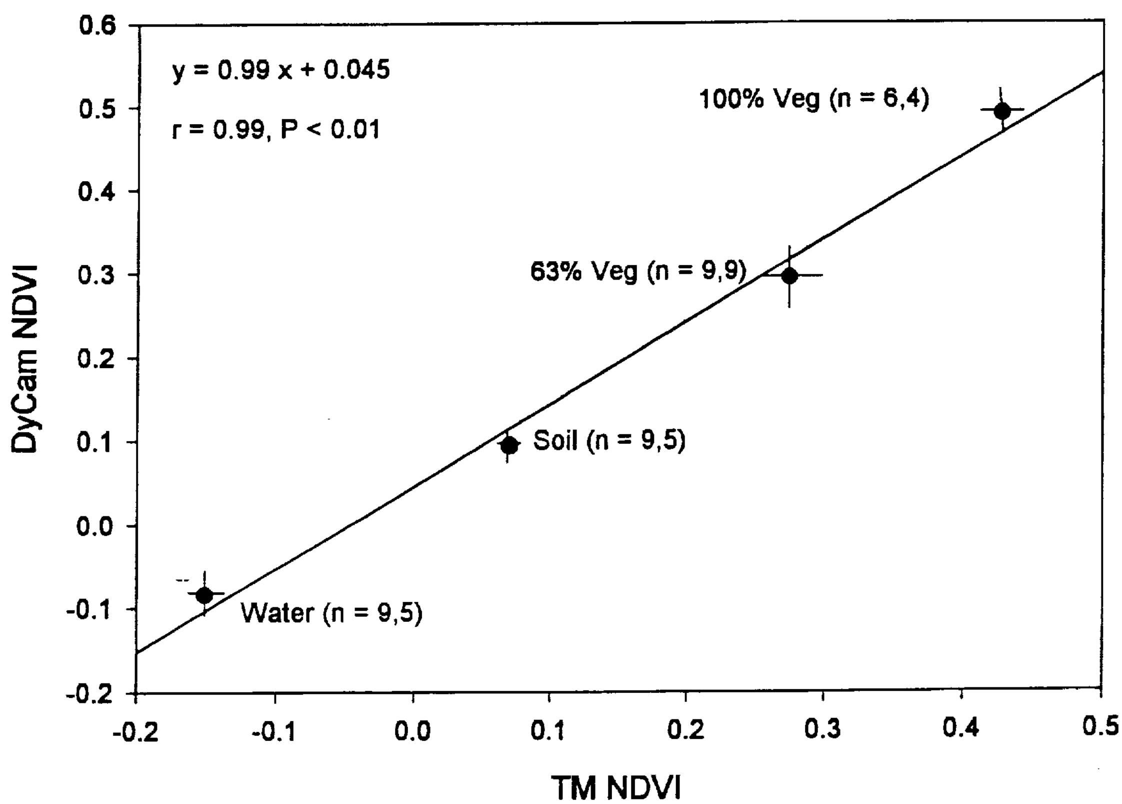


Figure 4. Linear regression of reflectance-based, NDVI values for different landcover classes on DyCam images taken over the Colorado River delta floodplain May 24, 1999 and a TM of the same landscape taken May 2, 1999. The regression line is based on mean values for each land cover class because the individual data points within each class were not necessarity co-located between DyCam and TM scenes.



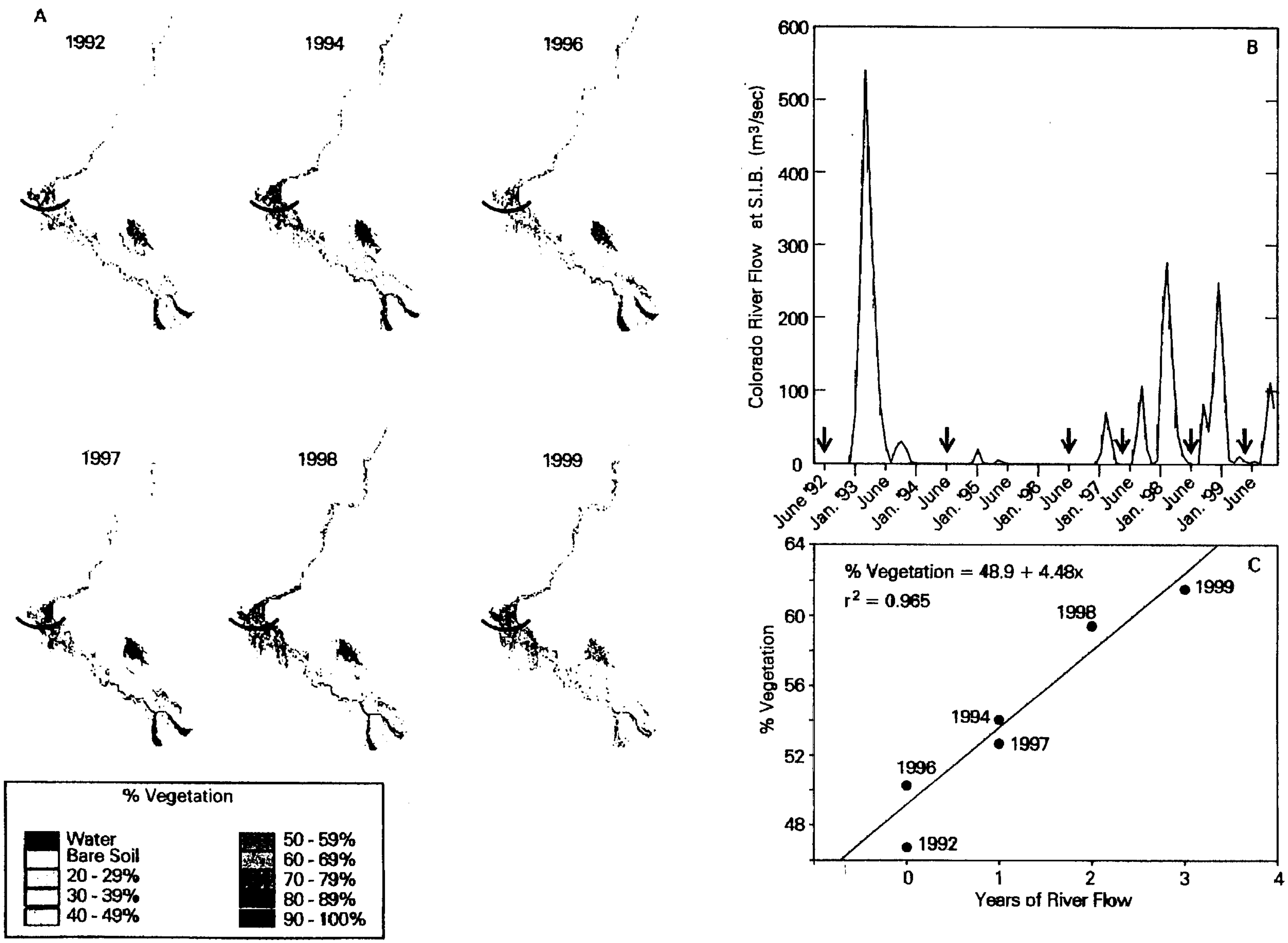


Figure 5 .Change analysis of vegetation intensity in the Colorado River delta as affected by flood releases from the United States to Mexico. (A) shows % vegetation in the cottonwood-willow zone determined by NDVI for images acquired before and after major flood flows since 1992 (arrows in B). Percent vegetation cover was moderately correlated with flow rate (data not shown) but was more strongly related to the number of years of flow prior to the summer the vegetation response was measured, regardless of flow intensity (C).